

# **WRF 4D-Var**

# **Where we are and where we go**

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# WRF 4D-Var developers

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*Acknowledgments.* The WRF 4D-Var development has been primarily supported by the Air Force Weather Agency. The Korean Meteorological Administration also funded some 4D-Var tasks.

# Outline

1. Introduction
2. WRF 4D-Var
3. Current status of WRF 4D-Var
4. Single ob experiments
5. Noise control
6. Meteorological tests
7. Work plan
8. Summary

# A short 4D-Var review

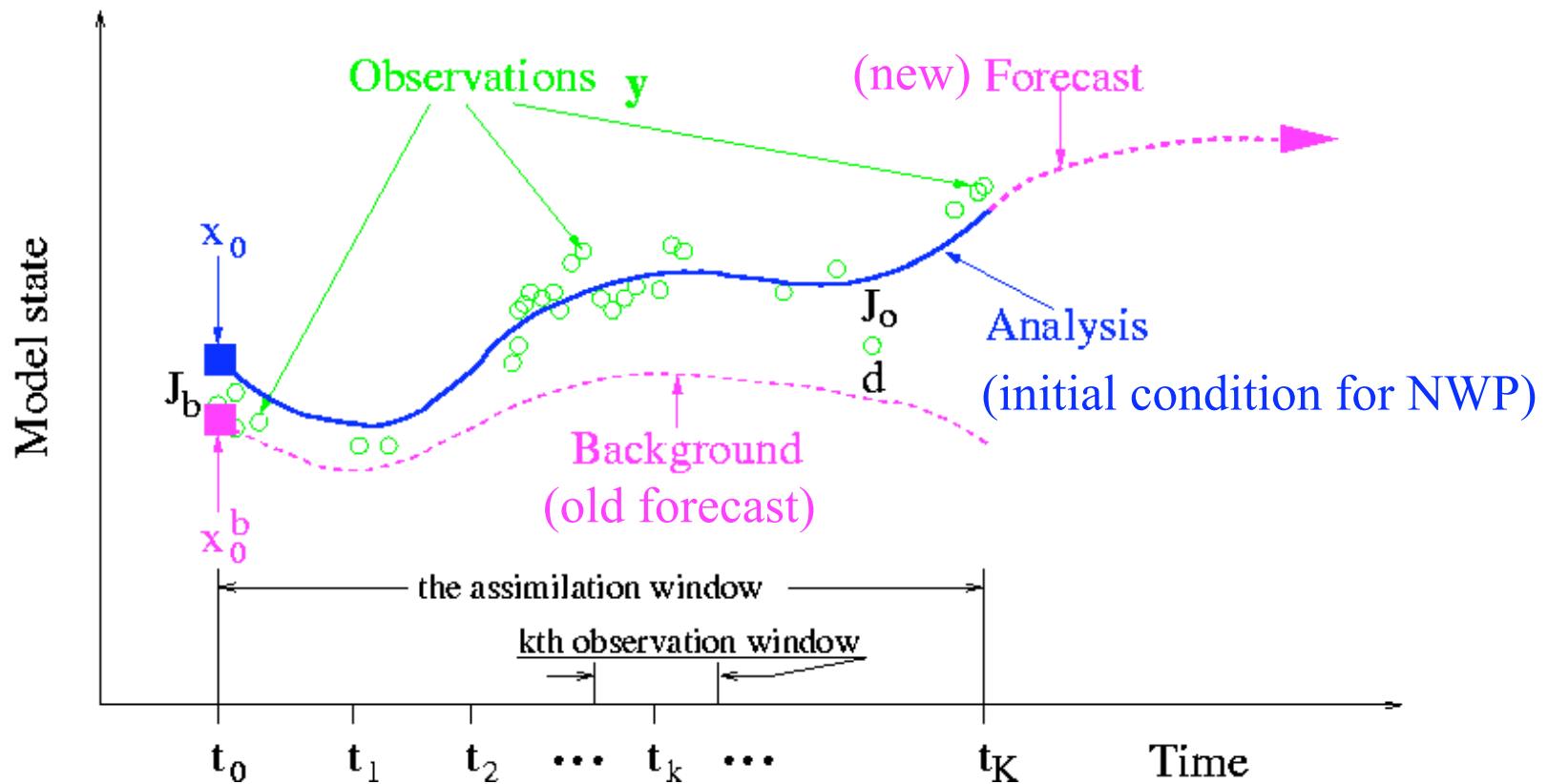
- The idea: Le Dimet and Talagrand (1986); Lewis and Derber (1985)
- Implementation examples:
  - Courtier and Talagrand (1990); a shallow water model
  - Thepaut and Courtier (1991); a multi-level primitive equation model
  - Navon, et al. (1992); the NMC global model
  - Zupanski M (1993); the Eta model
  - Zou, et al. (1995); the MM5 model
  - Sun and Crook (1998); a cloud model
  - Rabier, et al. (2000); the ECMWF model
  - [Huang, et al. \(2002\); the HIRLAM model](#)
  - Zupanski M, et al. (2005); the RAMS model
  - Ishikawa, et al. (2005); the JMA mesoscale model
  - [Huang, et al. \(2005\); the WRF model](#)
- Operation: ECMWF, Meteo France, JMA, UKMO, MSC.
- Pre-operation: HIRLAM

# Why 4D-Var?

- Use observations over a time interval, which suits most asynoptic data.
- Use a forecast model as a constraint, which ensures the dynamic balance of the analysis.
- Implicitly use flow-dependent background errors, which ensures the analysis quality for fast developing weather systems.

# Variational methods

$$J = \frac{1}{2} \left\{ (\mathbf{x} - \mathbf{x}_0^b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_0^b) + [H(M(\mathbf{x})) - \mathbf{y}]^T \mathbf{R}^{-1} [H(M(\mathbf{x})) - \mathbf{y}] \right\}$$



# Necessary components of 4D-Var

- $H$  observation operator, including the tangent linear operator  $\mathbf{H}$  and the adjoint operator  $\mathbf{H}^T$ .
- $M$  forecast model, including the tangent linear model  $\mathbf{M}$  and adjoint model  $\mathbf{M}^T$ .
- $\mathbf{B}$  background error covariance ( $N \times N$  matrix).
- $\mathbf{R}$  observation error covariance, which includes the representative error ( $K \times K$  matrix).

# WRF 4D-Var milestones

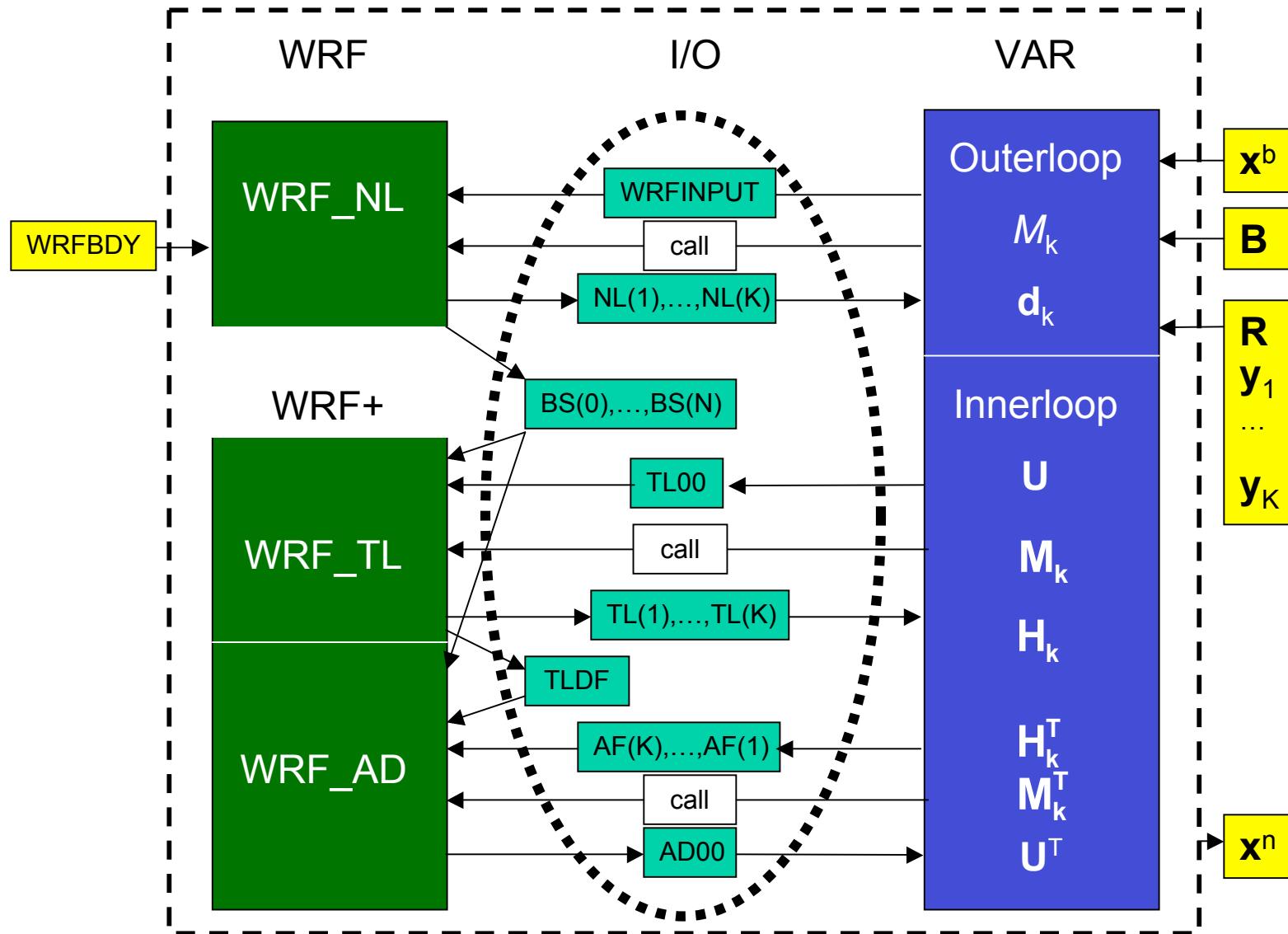
2003: WRF 4D-Var project.	?? FTE
2004: WRF SN (simplified nonlinear model). Modifications to WRF 3D-Var.	1.5 FTE
2005: TL and AD of WRF dynamics. WRF TL and AD framework. WRF 4D-Var framework.	1.5 FTE
2006: The WRF 4D-Var prototype. Single ob and real data experiments. Parallelization of WRF TL and AD. Simple physics TL and AD. JcDFI	2.5 FTE
2007: The WRF 4D-Var basic system.	2.5 FTE

Here we are!

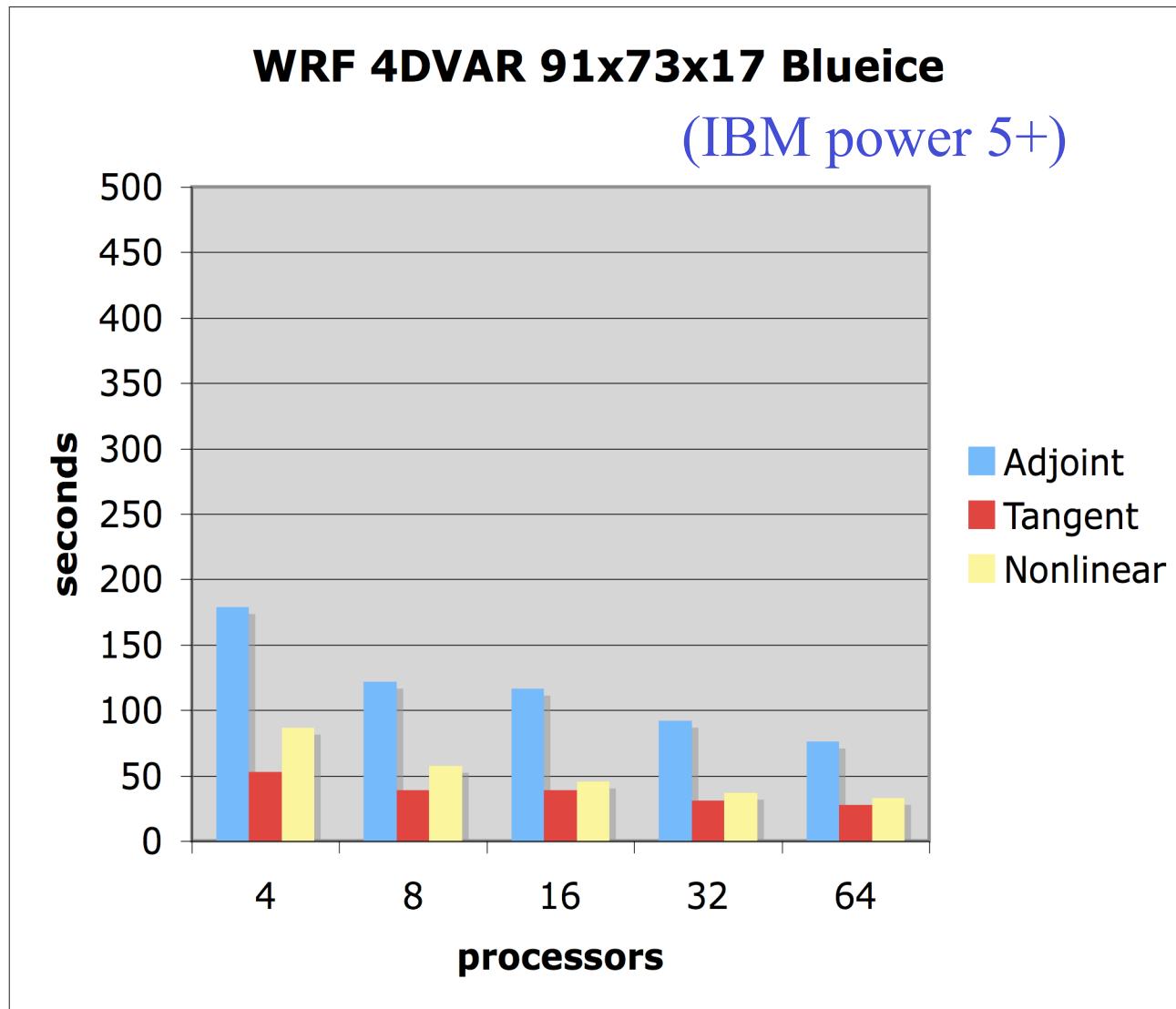
# The WRF 4D-Var basic system

- WRF, VAR and WRF+ parallelized in WRF Software Framework
  - WRF TL/AD (dyn + vdiff + lsc) produced using TAF ([www.fastopt.com](http://www.fastopt.com))
  - Parallel versions from hand-parallelized TAF output
- MPMD execution on processors sets under IBM load-leveler/LSF
- Coupling (coordination and exchange) among WRF, VAR and WRF+ through files

## Basic system: 3 exes, disk I/O, parallel, simple phys, JcDF



# Wall clock of 6 hours integration



# Single observation experiment

The idea behind single ob tests:

The solution of 3D-Var should be

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{B}\mathbf{H}^T [\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}]^{-1} [\mathbf{y} - H\mathbf{x}^b]$$

Single observation

$$\underline{\mathbf{x}^a - \mathbf{x}^b} = \mathbf{B}_i [\sigma_b^2 + \sigma_o^2]^{-1} [\mathbf{y}_i - x_i]$$

3D-Var  $\rightarrow$  4D-Var:  $\mathbf{H} \rightarrow \mathbf{HM}$ ;  $\mathbf{H}^T \rightarrow \mathbf{M}^T \mathbf{H}^T$

The solution of 4D-Var should be

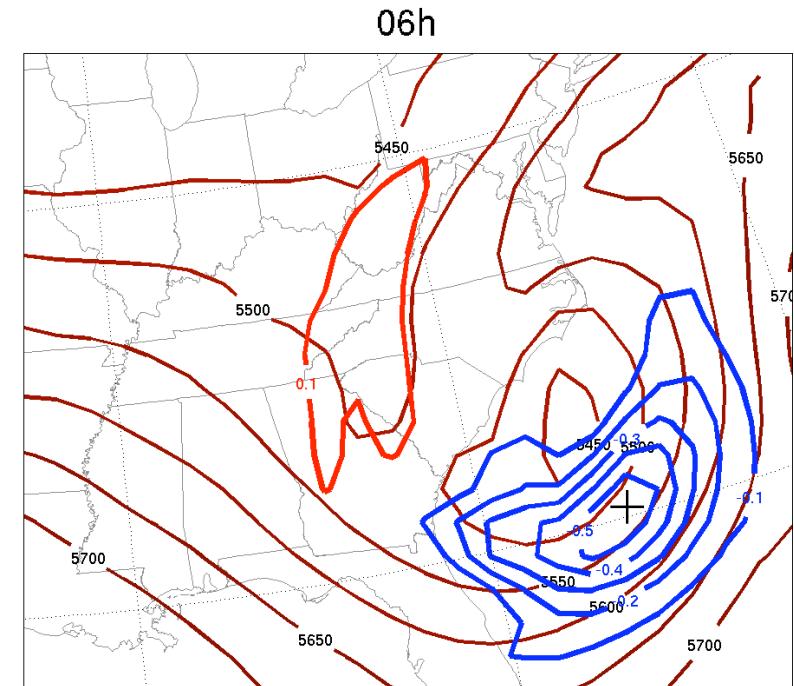
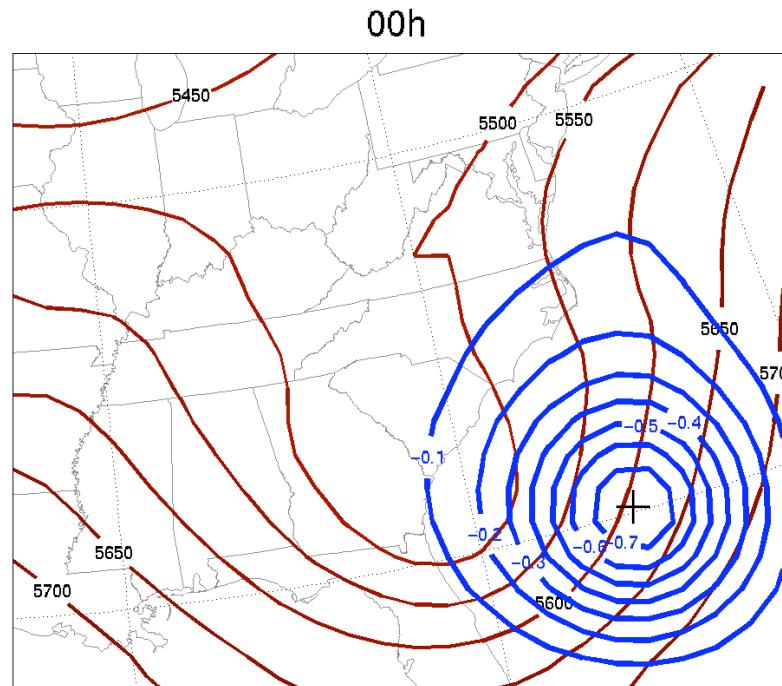
$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{B}\mathbf{M}^T \mathbf{H}^T [\mathbf{H}(\mathbf{MBM}^T)\mathbf{H}^T + \mathbf{R}]^{-1} [\mathbf{y} - H\mathbf{M}\mathbf{x}^b]$$

Single observation, solution at observation time

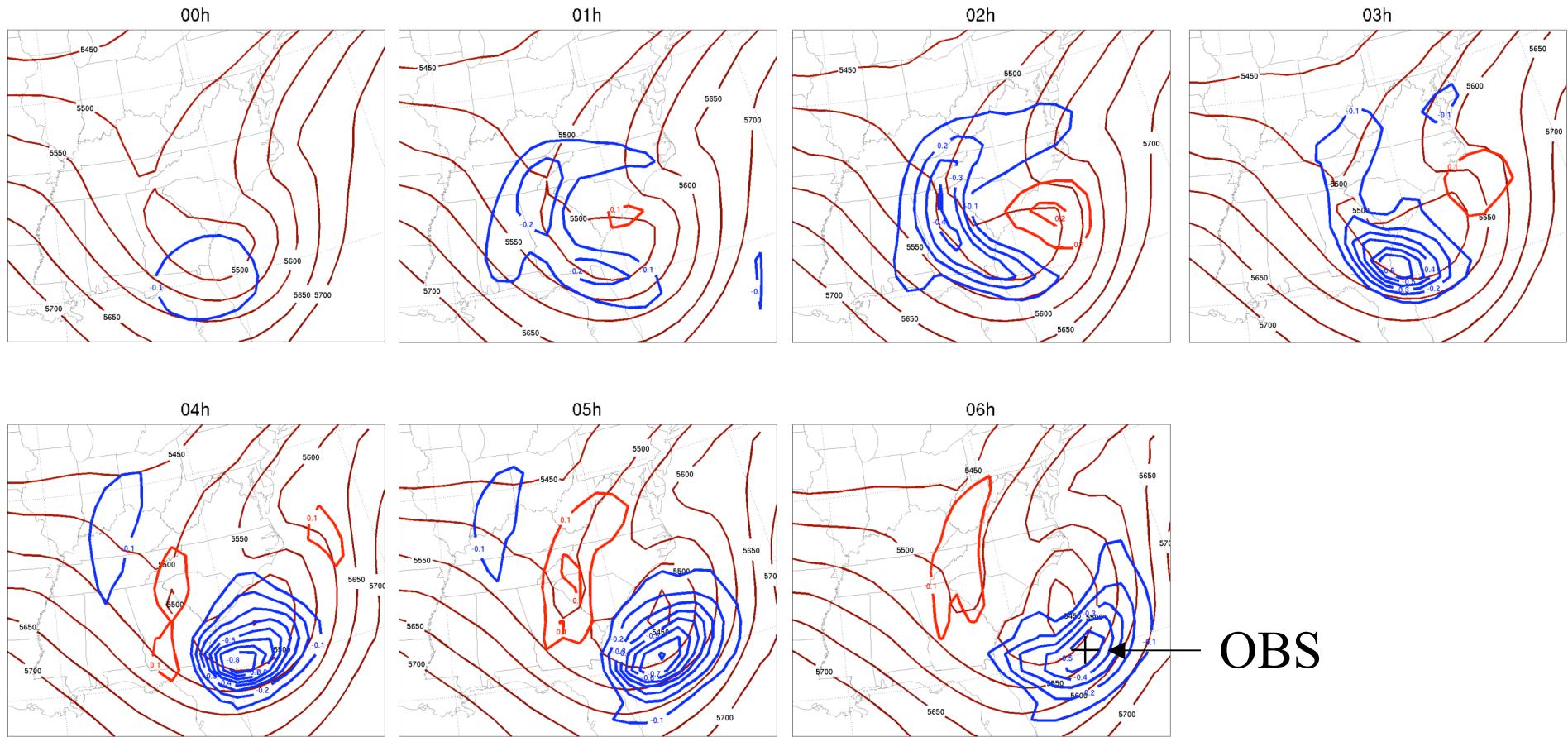
$$\underline{\mathbf{M}(\mathbf{x}^a - \mathbf{x}^b)} = (\mathbf{MBM}^T)_i [\sigma_b^2 + \sigma_o^2]^{-1} [\mathbf{y}_i - x_i]$$

# Analysis increments of 500mb $\theta$

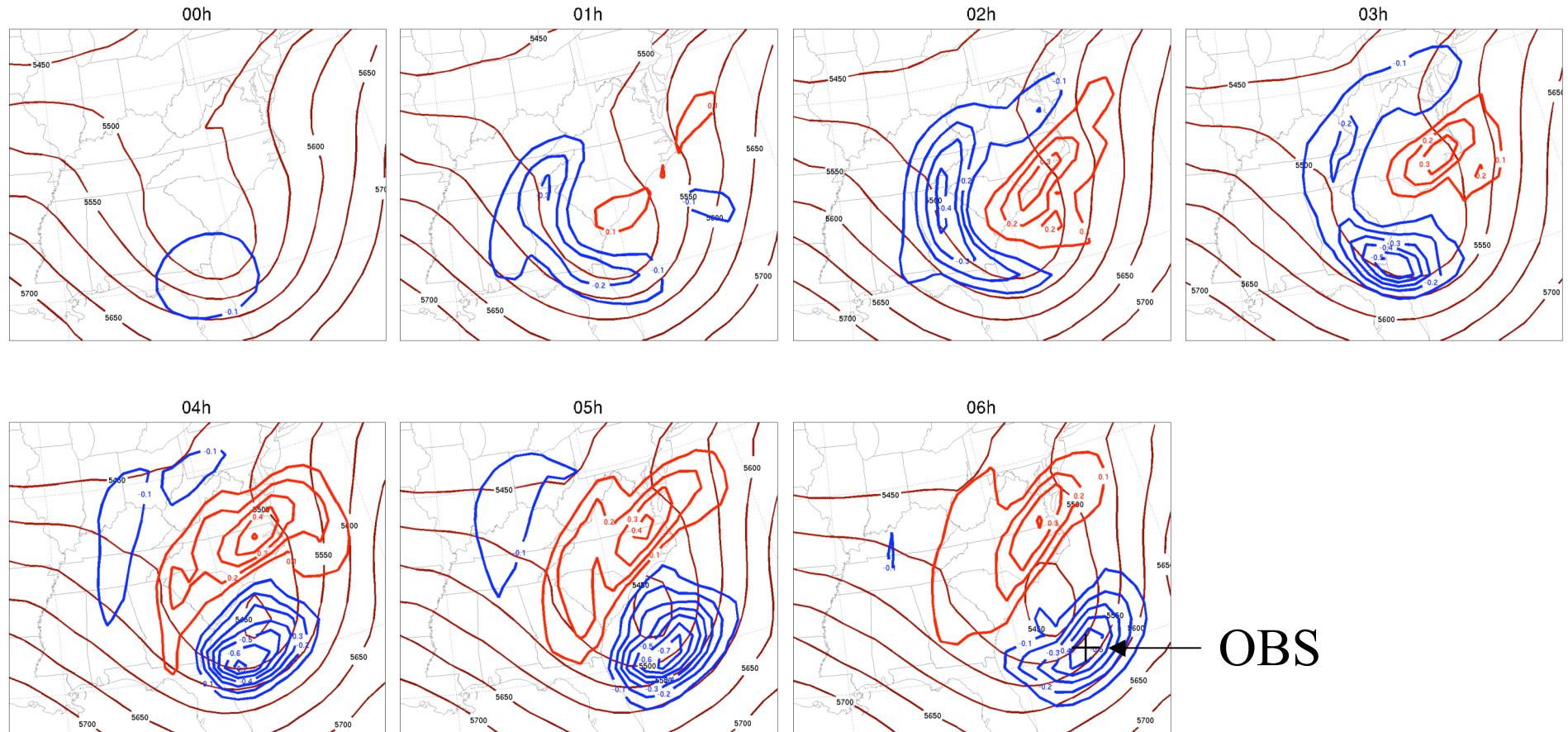
from 3D-Var at 00h and from 4D-Var at 06h  
due to a 500mb T observation at 06h



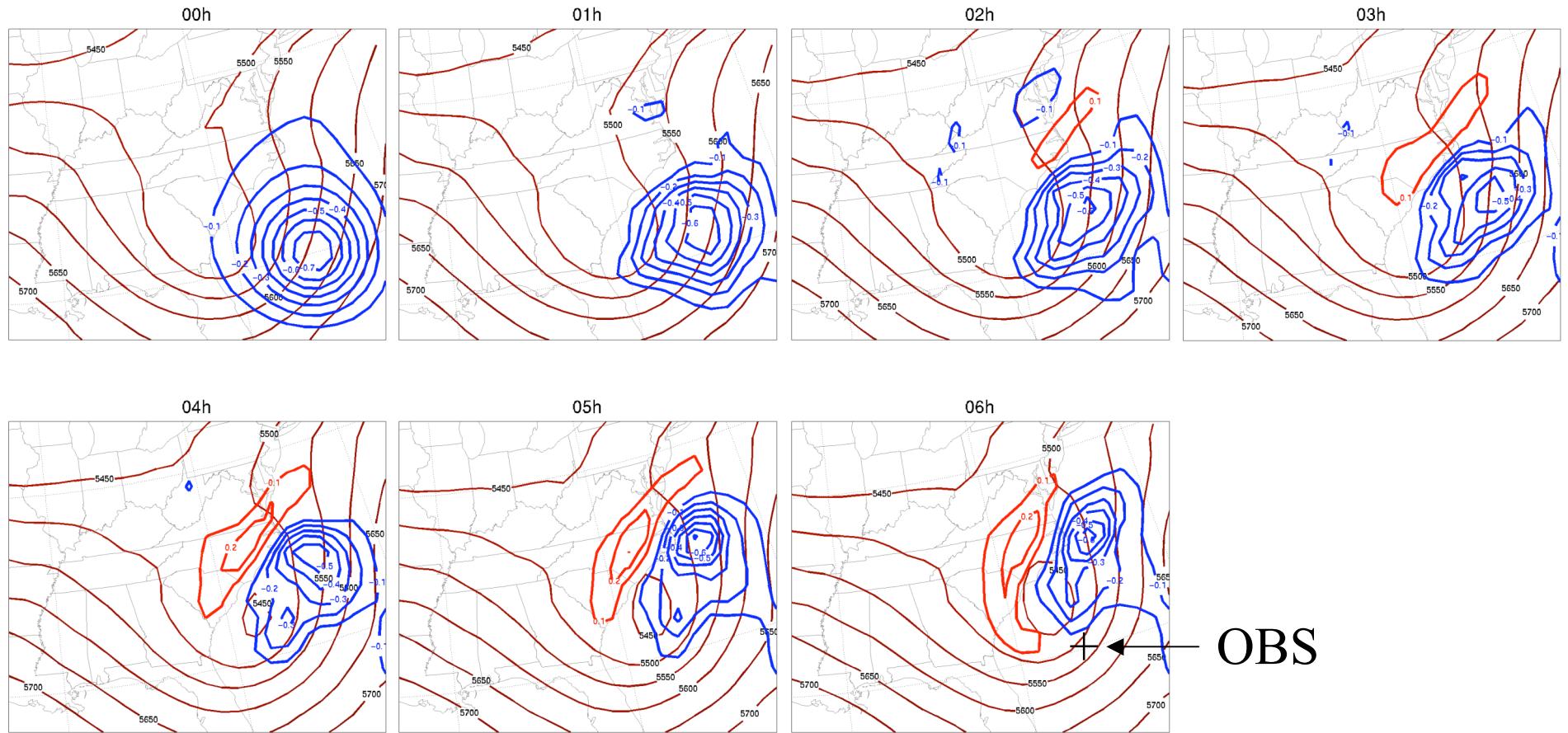
## 500mb $\theta$ increments at 00,01,02,03,04,05,06h to a 500mb T ob at 06h



500mb  $\theta$  difference at 00,01,02,03,04,05,06h from  
two nonlinear runs (one from background; one from 4D-Var)



500mb  $\theta$  difference at 00,01,02,03,04,05,06h from  
two nonlinear runs (one from background; one from FGAT)



# JcDF in WRF-Var4d

## Weak constraint for noise control

Before:  $J = J_o + J_b$

$$J_b(\mathbf{x}_0) = \frac{1}{2} [(\mathbf{x}_0 - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x}_0 - \mathbf{x}_b)]$$

$$J_o(\mathbf{x}_0) = \frac{1}{2} \sum_{k=1}^K [(\mathbf{H}_k \mathbf{x}_k - \mathbf{y}_k)^T \mathbf{R}^{-1} (\mathbf{H}_k \mathbf{x}_k - \mathbf{y}_k)]$$

After:  $J = J_o + J_b + J_c$

$$\begin{aligned} J_c(\mathbf{x}_0) &= \frac{\gamma_{df}}{2} \left[ (\delta\mathbf{x}_{N/2} - \delta\mathbf{x}_{N/2}^{df})^T \mathbf{C}^{-1} (\delta\mathbf{x}_{N/2} - \delta\mathbf{x}_{N/2}^{df}) \right] \\ &= \frac{\gamma_{df}}{2} \left[ \left( \delta\mathbf{x}_{N/2} - \sum_{i=0}^N f_i \delta\mathbf{x}_i \right)^T \mathbf{C}^{-1} \left( \delta\mathbf{x}_{N/2} - \sum_{i=0}^N f_i \delta\mathbf{x}_i \right) \right] \\ &= \frac{\gamma_{df}}{2} \left[ \left( \sum_{i=0}^N h_i \delta\mathbf{x}_i \right)^T \mathbf{C}^{-1} \left( \sum_{i=0}^N h_i \delta\mathbf{x}_i \right) \right] \end{aligned}$$

where:

$$h_i = \begin{cases} -f_i, & \text{if } i \neq N/2 \\ 1 - f_i, & \text{if } i = N/2 \end{cases}$$

# Performance of JcDF

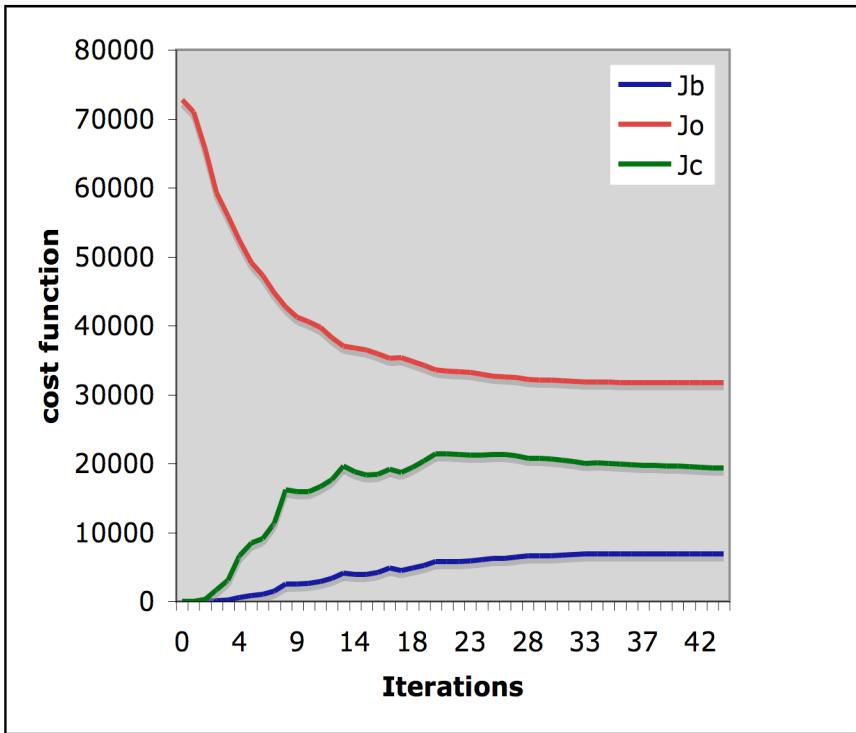


Figure 3 Cost functions without JcDF ( $\text{gama}=0.1$ )

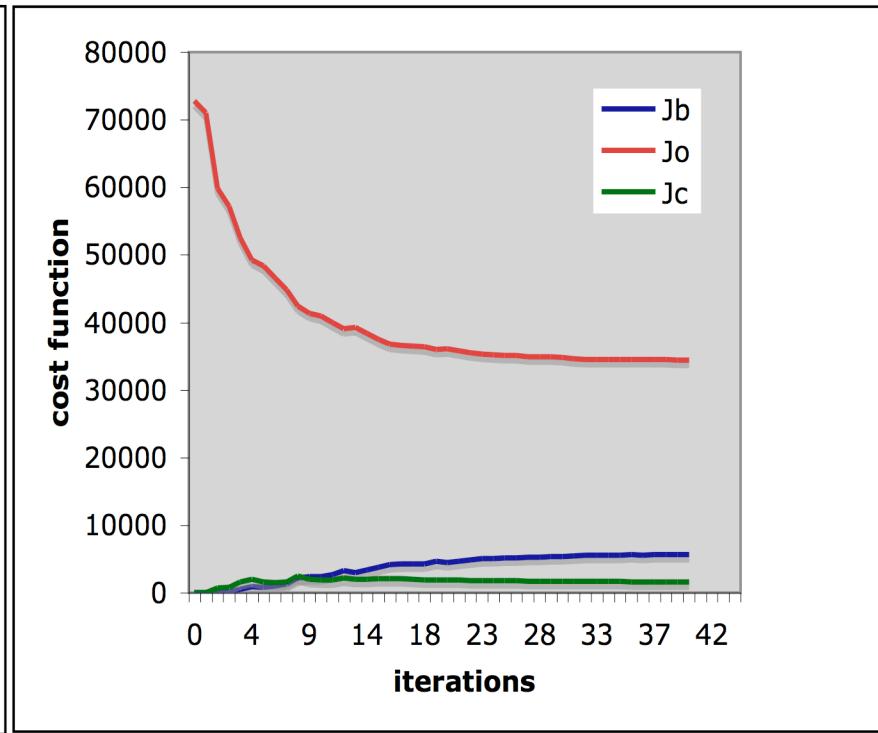
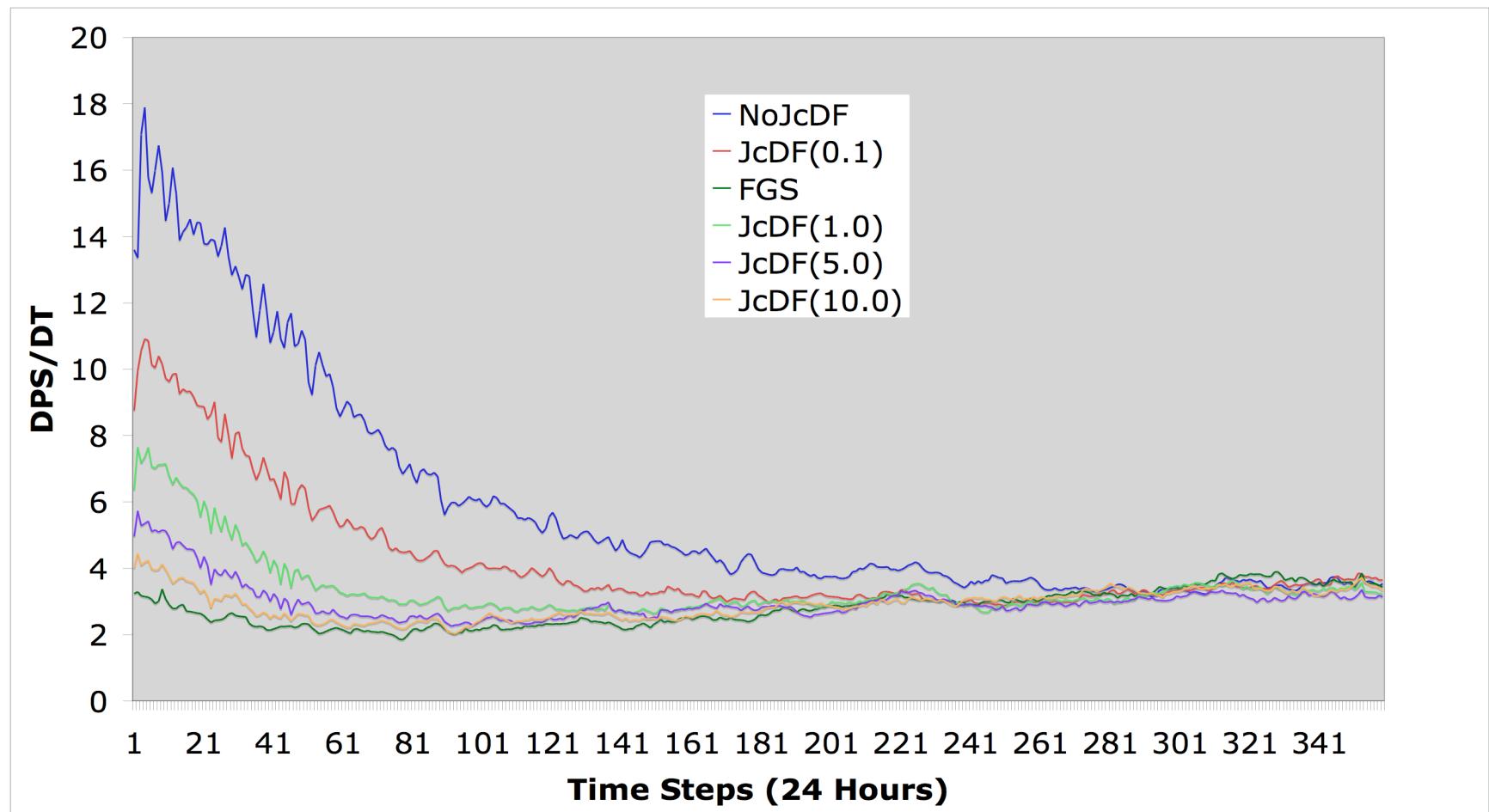


Figure 4 Cost functions with JcDF ( $\text{gama}=0.1$ )

# 3-hour Surface Pressure Tendency



# Meteorological tests

1. Typhoon Haitang
2. KMA Heavy Rain (KMA funded project)

# Real Case: Typhoon Haitang

## Experimental Design

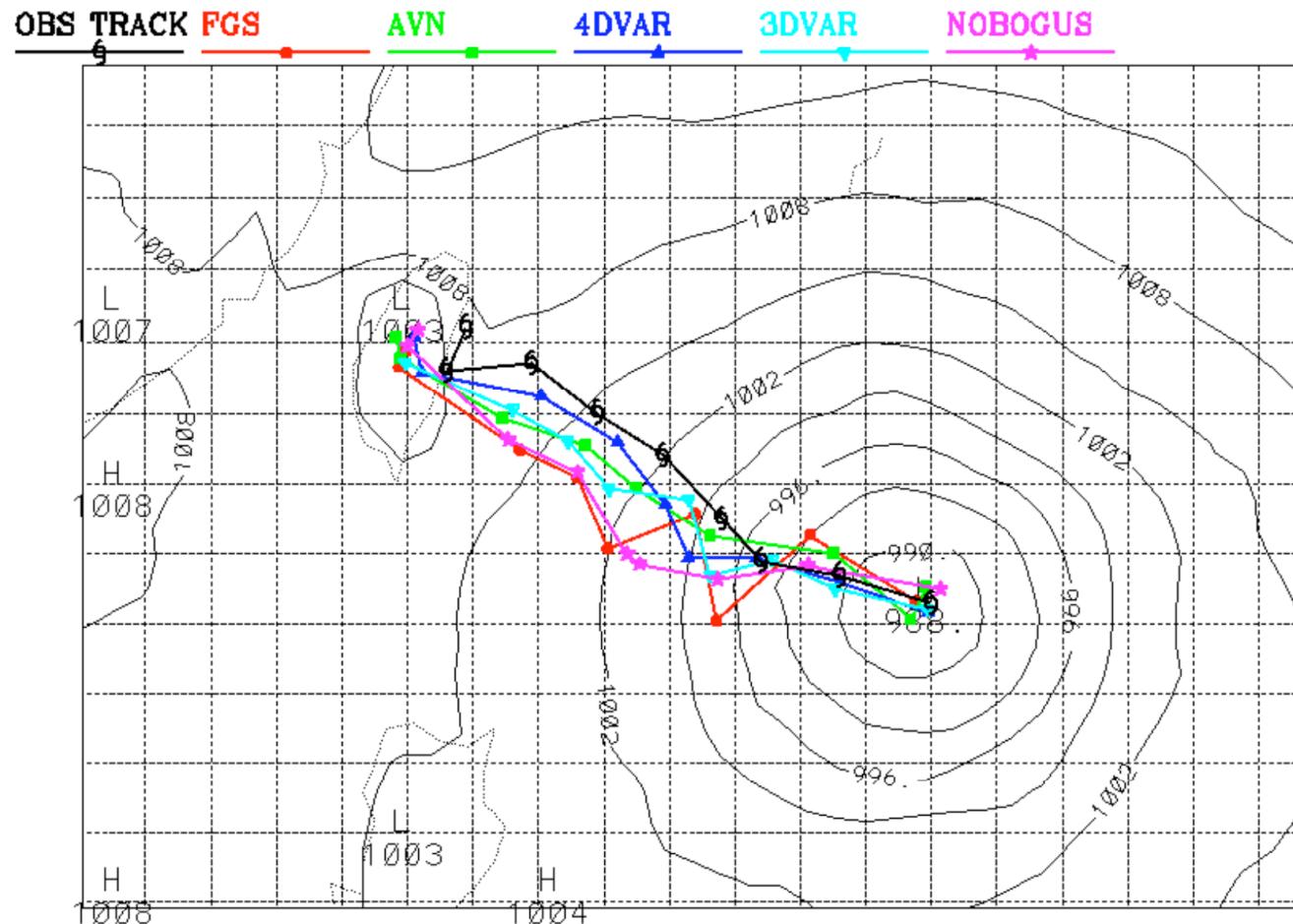
- Domain configuration: 91x73x17, 45km
- Observations from Taiwan CWB operational database.
- Experiments are conducted before Haitang's landfall at 0000 UTC 18 July 2005.
  - **FGS** – forecast from the background [The background fields are 6-h WRF forecasts from National Center for Environment Prediction (NCEP) GFS analysis.]
  - **AVN** - forecast from the NCEP AVN analysis
  - **3DVAR** – forecast from cycling WRF-Var3d
  - **4DVAR** – forecast from cycling WRF-Var4d
  - NOBOGUS - 4D-Var, but withheld BOUGS data

# Observations used in a 4D-Var experiment

Table 1. The numbers of different observation types assimilated by WRF 4D-Var at 0600 UTC 16 July.

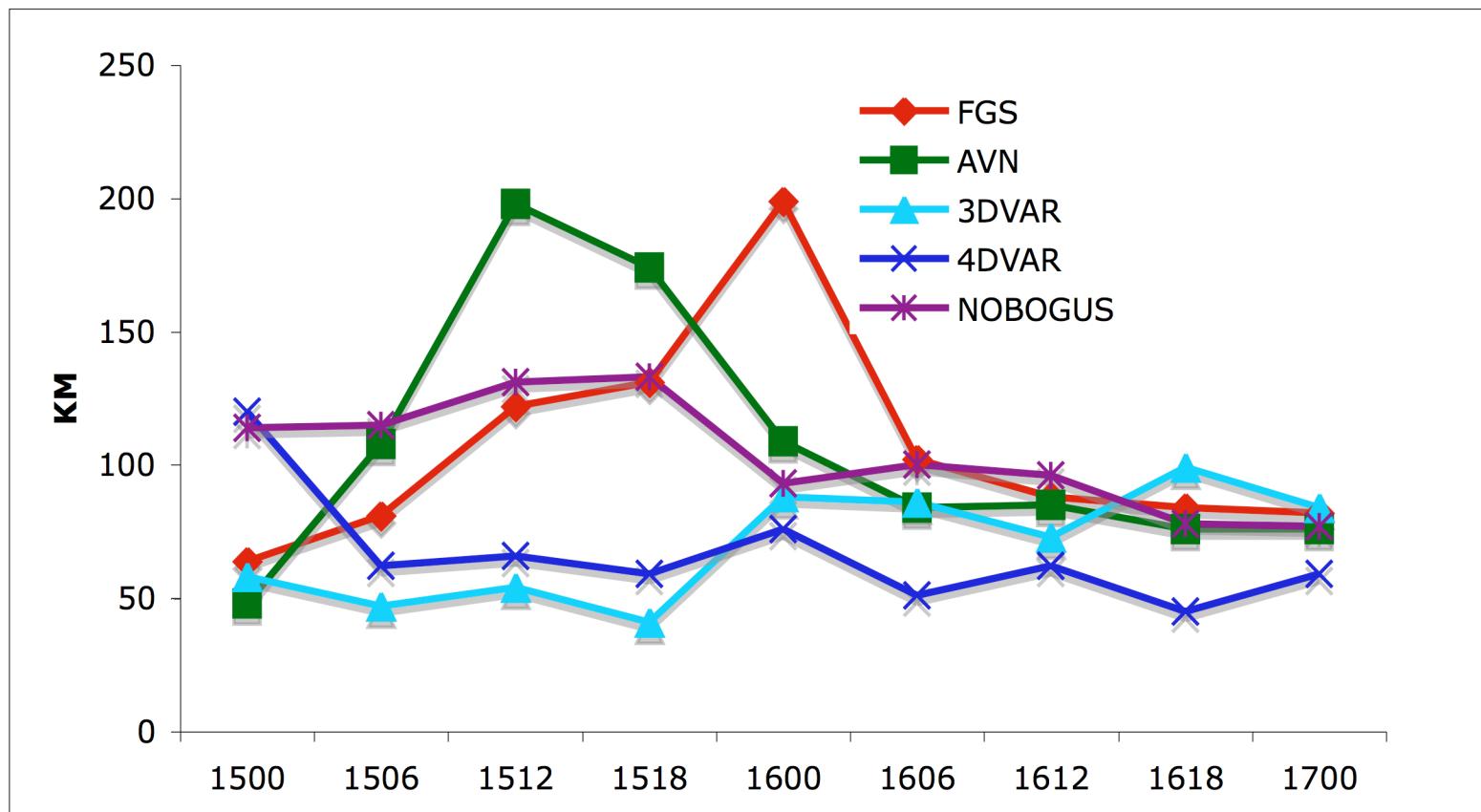
	<b>U(m/s)</b>	<b>V(m/s)</b>	<b>T(K)</b>	<b>P(Pa)</b>	<b>Q(kg/kg)</b>	<b>DZ(m)</b>	<b>REF(m)</b>
<b>TEMP</b>	858	857	1054		841		
<b>TEMPsurf</b>	9	10	12	12	12		
<b>SYNOP</b>	229	232	240	237	238		
<b>GEOAMV</b>	2569	2569					
<b>AIREP</b>	932	933	947				
<b>PILOT</b>	124	121					
<b>METAR</b>	128	130	154		144		
<b>SHIP</b>	55	58	64	64	58		
<b>GPSREF</b>							162
<b>SATEM</b>						851	
<b>QSCAT</b>	2597	2610					
<b>BUOY</b>	66	65		65			
<b>BOGUS</b>	1200	1200	788	788	80		

# Typhoon track verification



2005071606 SLP FROM FGS

# The track error in km averaged over 48 h

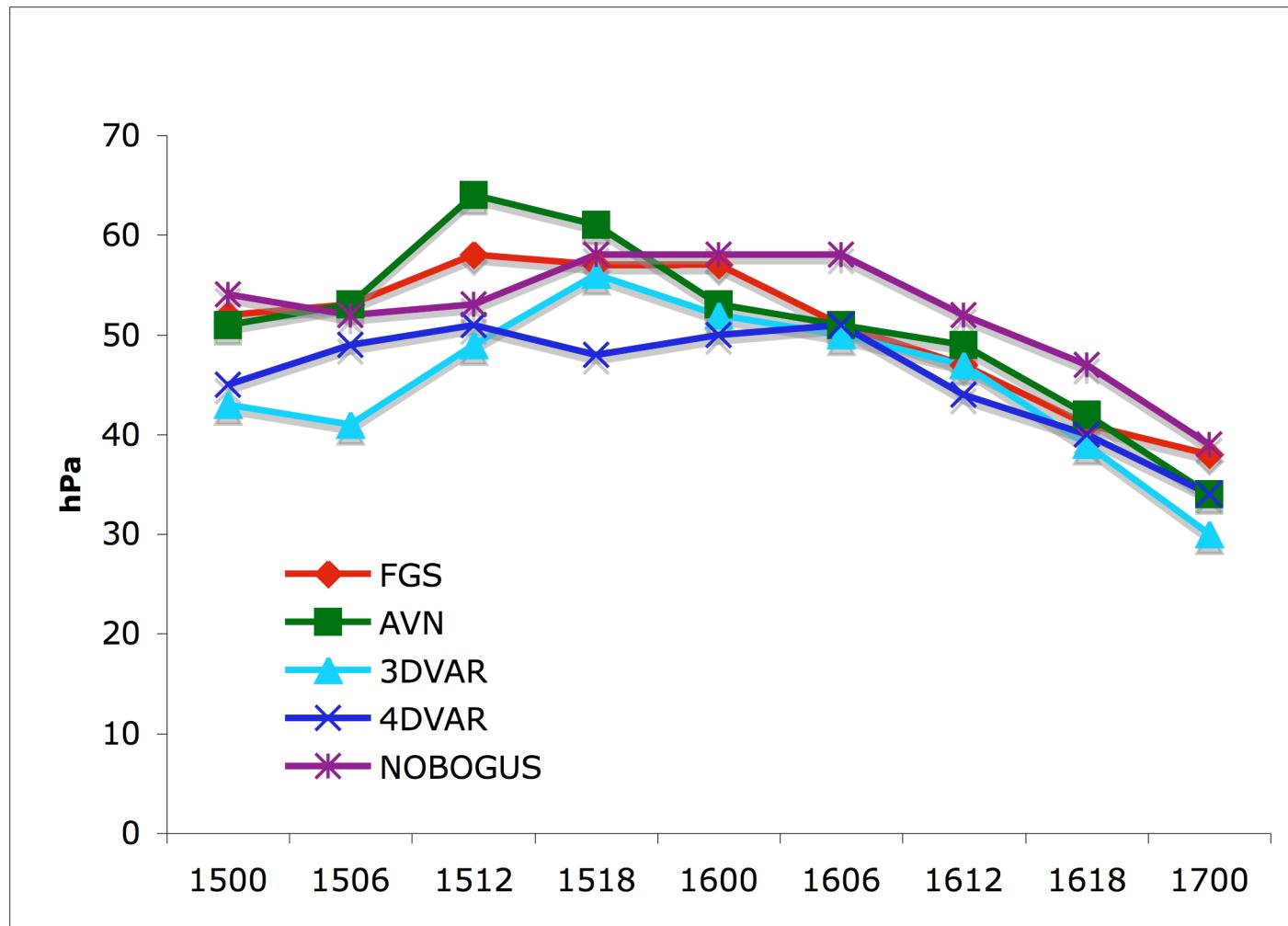


# Typhoon Track Verification

Table 2 The track error in km averaged over 48 h (unit: KM)

Time	FGS	AVN	3DVAR	4DVAR	NOBOGUS
<b>1500</b>	64	<b>48</b>	58	120	114
<b>1506</b>	81	108	<b>47</b>	62	115
<b>1512</b>	122	198	<b>54</b>	66	131
<b>1518</b>	131	174	<b>41</b>	59	133
<b>1600</b>	199	109	88	<b>76</b>	93
<b>1606</b>	102	84	86	<b>51</b>	100
<b>1612</b>	88	85	73	<b>62</b>	96
<b>1618</b>	84	76	99	<b>45</b>	78
<b>1700</b>	82	76	84	<b>59</b>	77
Ave	106	106	70	<b>67</b>	104

# Intensity error in hPa averaged over 48 h



# Typhoon Intensity Verification

Time	FGS	AVN	3DVAR	4DVAR	NOBOGUS
1500	52	51	43	45	54
1506	53	53	41	49	52
1512	58	64	49	51	53
1518	57	61	56	48	58
1600	57	53	52	50	58
1606	51	51	50	51	58
1612	47	49	47	44	52
1618	41	42	39	40	47
1700	38	34	30	34	39
Ave	50.44	50.89	45.22	45.78	52.33

# Summary of Typhoon Haitang Experiments

- Better track forecasts from 4D-Var (compared to those from 3D-Var)
- Comparable central pressure forecasts
- Bogus data are important

# Real Case: KMA Heavy Rain

Period: 12 UTC 4 May - 00 UTC 7 May, 2006

Assimilation window: 6 hours

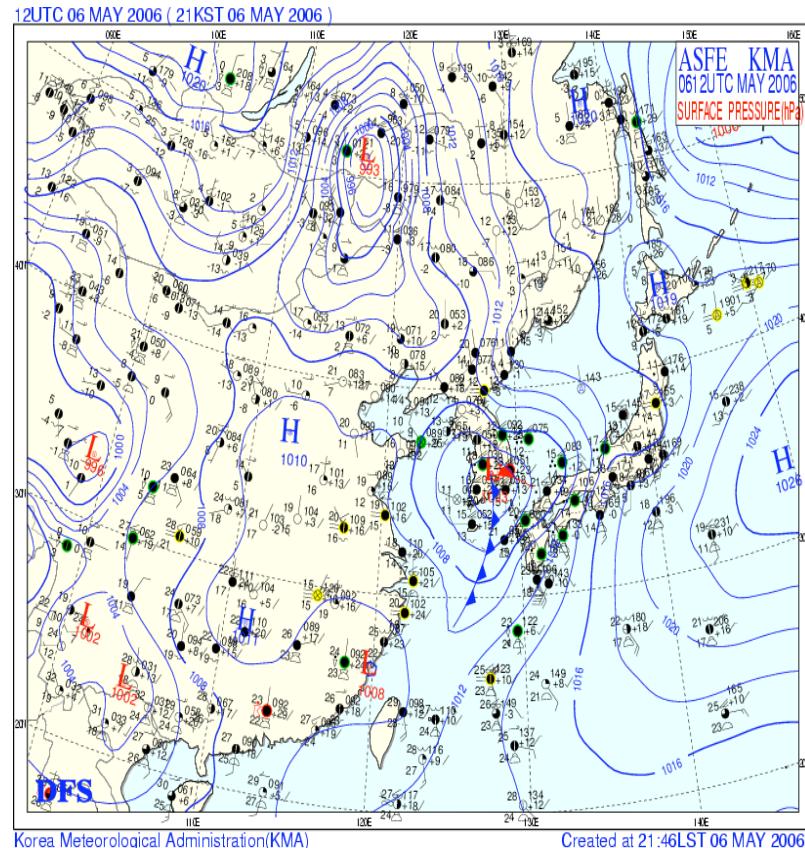
Cycling

All KMA operational data

Grid : 60x54x31

Resolution : 30km

Domain size: the same as the  
KMA perational 10km domain.  
(from the KMA project)



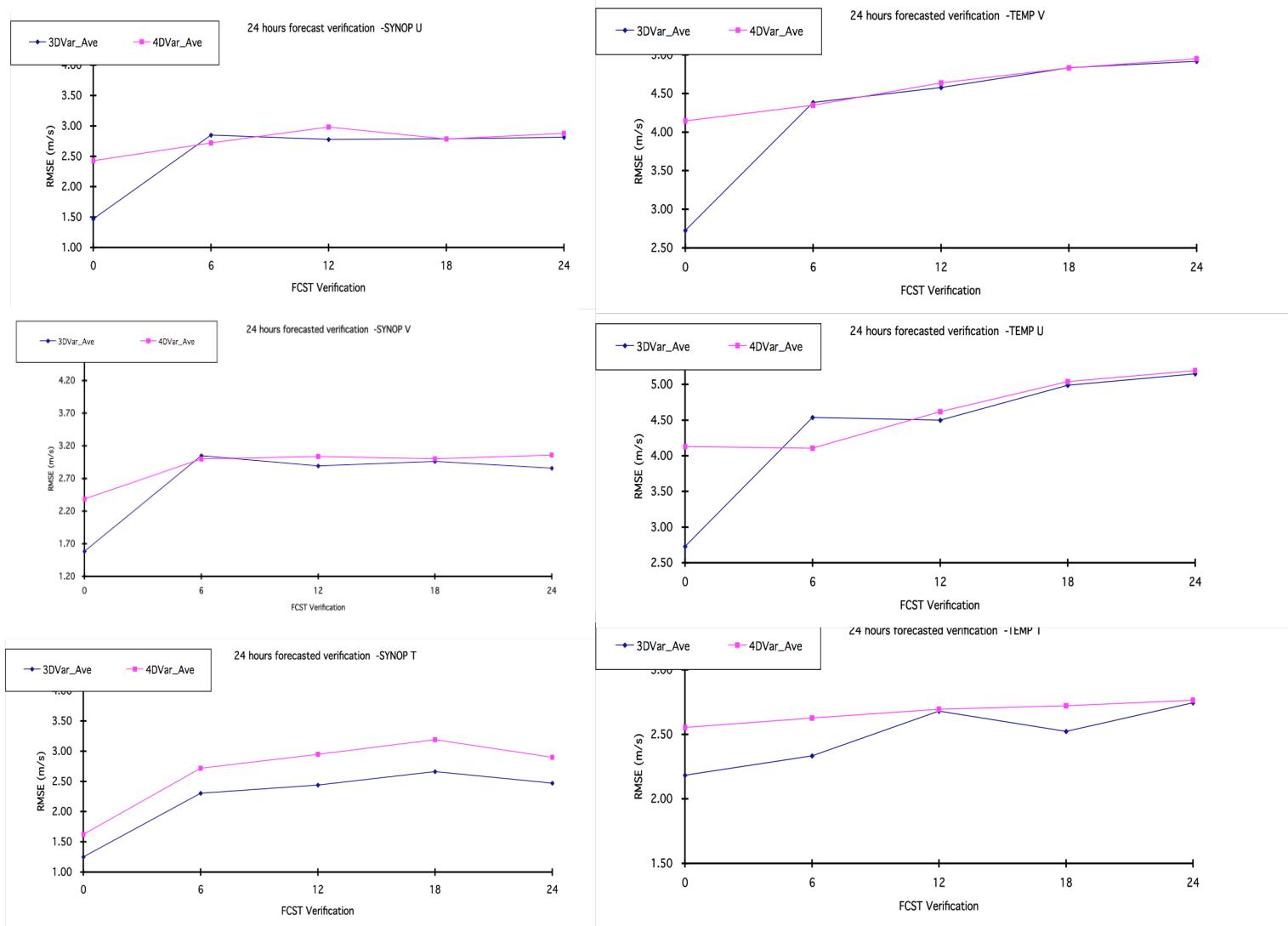
# Observations used in 3D-Var

	<b>U wind</b>	<b>V wind</b>	<b>Temperature</b>	<b>Pressure</b>	<b>Water vapor</b>
<b>SOUND</b>	459	464	519	-	385
<b>SONDE_SFC</b>	14	15	15	15	15
<b>SYNOP</b>	67	59	73	71	72
<b>GEOAMV</b>	74	76	-	-	-
<b>PILOT</b>	182	195	-	-	-
<b>METAR</b>	559	551	614	33	36
<b>SHIP</b>	1	1	2	2	1

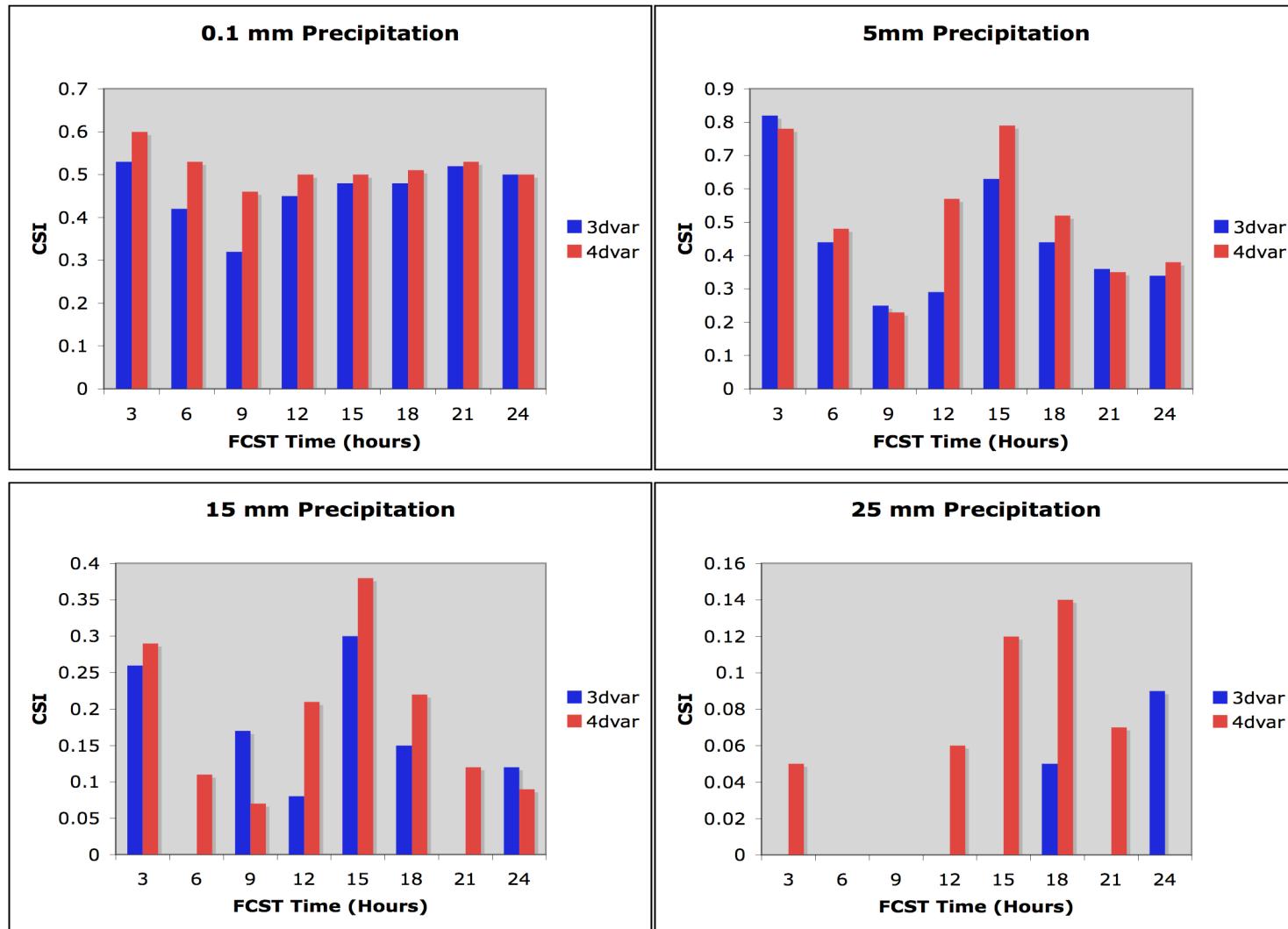
# Observations used in 4D-Var

	<b>U wind</b>	<b>V wind</b>	<b>Temperature</b>	<b>Pressure</b>	<b>Water vapor</b>
<b>SOUND</b>	456	461	519	-	384
<b>SONDE_SFC</b>	14	14	15	14	15
<b>SYNOP</b>	253	212	268	191	204
<b>GEOAMV</b>	-	-	-	-	-
<b>PILOT</b>	185	194	-	-	-
<b>METAR</b>	2636	2402	2957	218	240
<b>SHIP</b>	1	1	2	2	1

# Observations Verification



# Precipitation Verification



# Summary of the Heavy Rain Experiments

- T: 3D-Var better
- u,v: comparable
- Precipitation: 4D-Var significantly better

# Work plan for 2007

1. Multi-incremental formulation
2. Optimization
3. Convection
4. Meteorological tests
5. Lateral boundary control
6. Analysis on C-grid

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